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Smart and Physically-Based Navigation in 3D Geovirtual Environments

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Abstract

This paper describes an approach for smart and physically-based navigation, which aims at supporting effective and intuitive user interactions with 3D geovirtual environments (GeoVEs). The approach is based on two aligned concepts: 1) All navigation techniques are controlled by constraints that ensure user orientation and avoid "getting lost" situations. 2) All navigation techniques are handled in a time-coherent way achieving steady, continuous user movements using a physically-based motion model. Based on these concepts, we demonstrate several ways to improve commonly used navigation techniques for geovirtual environments.

Keywords: 3D Navigation, Physical Motion Model, Geovisualization, Virtual Environments.

1. Introduction

One of the most important aspects of human-computer interactions in virtual environments represents the effectiveness and intuition of the underlying navigation tools controlled by the users. Particularly in geovirtual environments, navigation represents a key functionality because "the acquisition of spatial knowledge, essential for wayfinding, is primarily based on direct environmental experience, which is usually gained via movement" [6].

This paper presents an approach towards system-assisted 3D navigation based on smart constraints and a physically-based motion model. The navigation techniques presented are intended for real-time geovirtual 3D environments such as virtual terrain models, city models, and landscape models. The techniques are targeted at non-immersive environments and user interaction by regular input devices such as 2D mouse, space mouse, and keyboard.

As their key characteristics, the navigation techniques can be classified as smart and physically-based. With "smart" we refer to techniques that are aware of confusing, disorienting viewing situations and provide means to circumvent them. In addition, the navigation techniques apply a physically-based model of the 3D motion to ensure steady, continuous user movements and to decouple the motion process from the handling of hardware and user events.

1.1 Disorientation in Virtual 3D Environments

Disorientation represents one of the core problems for the usability of virtual environments: Users frequently get lost in the virtual space, that is, they lose their sense of position, relations, and orientation. As Fuhrmann and MacEachren point out [5], "core problems for users of these desktop GeoVEs are to navigate through, and remain oriented in, the display space and to relate that display space to the geographic space it depicts." Particularly, the "end-of-world" problem is critical, that is, if a user exceeds the virtual world's boundaries and reaches an undefined area. Disorientation affects both inexperienced users as well as experienced users. The former frequently need to restart or to cancel ongoing activities, for the latter disorientation hinders effective working in virtual environments. Burtnyk et al. [2] describes further problems such as "a user may […] view the model from awkward angles that present it in poor light, miss seeing important features, experience frustration at controlling their navigation, etc.".

Smart navigation techniques provide a solution to the disorientation problem. The key idea is to apply constraints that limit camera control in a way that the resulting view is guaranteed to contain a significant amount of orientation-supporting information. In addition, navigation techniques can take into account meta information about the environment and its objects to favorite important aspects, e.g., landmarks or areas of interest.

Although smart navigation techniques constrain user interactions, they must provide a sense of direct control to the user and operate as comprehensible as possible. Otherwise, constraints might cause the user to fight helplessly against a limitation that the user does not understand. Additionally, the user should realize the camera control as time-coherent and physically sound – unsteady and discontinuous motions, which would lead to distraction, have to be avoided by an independent physically-based camera model.

1.2. Unsteady and Discontinuous Camera Motion

An unsteady and discontinuous camera motion causes serious problems for interactive applications: If the view of a subsequent frame is not visually coherent to the previous frame, the user becomes not aware of the actual camera movement. In the more harmless case of a jerky motion the user is disturbed in performing a task within the virtual environment. In practice, the problem of abrupt changes is often circumvented by restricting the camera to slow movements, which leads to a disadvantageous compromise between smooth movement and the capability of fast interaction.

To facilitate the design of navigation techniques and constraints we propose an independent physically-based camera motion subsystem, in which the camera is modeled as a real, physical object situated in the virtual world experiencing realistic physical forces. This approach allows us to guarantee smooth movements when abrupt changes in position or velocity occur, for example, caused by directly mapping input events to camera settings or by collisions between camera and scene objects. Minimizing distracting discontinuities in the camera movement as well as reducing delays due to uncomfortable slow movement helps the user in concentrating on the intended tasks.

2. Related Work

2.1 Navigation Techniques

There are several established navigation techniques for virtual environments, which can be classified into egocentric and exocentric frame of reference [8] and distinguished according to the task they are suited for [16].

With the *Pedestrian navigation* the user explores a virtual environment from the point of view of a virtual avatar, which can walk in four directions and rotate the gaze around two axes using the mouse. This technique has become quite popular due to its frequent use in computer games. Similarly, the *Flyer navigation* controls a virtual flying vehicle. The user manipulates the speed of the forward/backward movement and the rotation around the world's up-vector. In addition, the flying vehicle allows to change the height or to tilt the view direction. The Flyer navigation is frequently used in geovirtual environments. Both Pedestrian and Flyer navigations are well suited for presentations and entertainment applications. The *Click-and-Fly navigation* allows a directed flight to a selected point of interest [14]. Navigation can be further improved by a *Landmark navigation*, which calculates on-demand camera paths from the current position to certain pre-defined viewpoints [10,15].

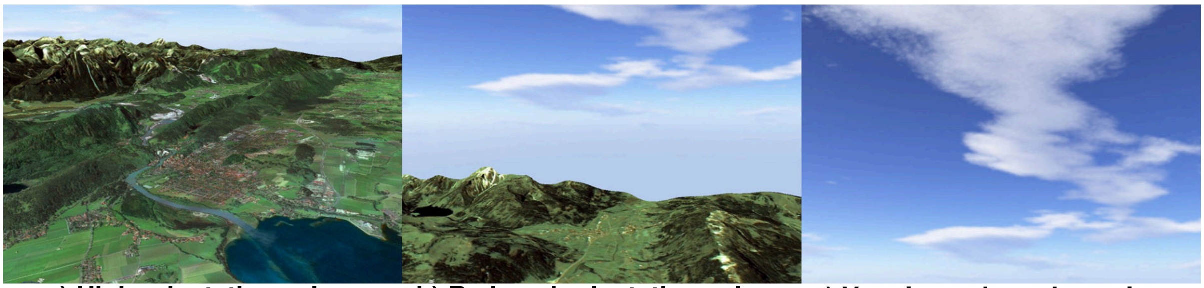
For the task of examination, the *Trackball navigation* is preferable. The user moves the camera on the surface of a virtual sphere. It is usually combined with the *Zoom navigation*, which allows the user to control the distance of the camera to a focus point. This point is determined by shooting a ray from the camera position towards the view direction. With the *Focus navigation* the user selects a point in the virtual environment that becomes the new focus point. The technique rotates the camera in such way that the focus point moves into the center of the viewplane during a short animation period. There is a large number of other useful techniques, see [4,8,12,16] for an overview.

2.2 Constrained Navigation

Guided navigation has been applied successfully for supporting user orientation, user experience, and the creation of the user's cognitive map. Galyean proposed the river analogy [7]: The user is guided by a predefined path and controls the gaze direction along with slight deviations away from the path. Hanson and Wernert extended this concept to guide manifolds [9]. Using 2D input devices the user moves on a designer-provided surface. The remaining degrees of freedom are controlled by predefined guide fields according to the camera position. In [20] this method has been extended and applied to collaborative virtual environments. Burtnyk et al. [2] developed an authoring tool for camera movement called StyleCam that allows for continuous and seamless transition between the camera's spatial-control and its temporal-control of animation; they apply user-defined surfaces to constrain the camera movement. The attentive camera [11] addresses the problem of guiding the view direction without distracting the user from the intended walk direction. Kiss and Nijhold [13] presented a system that alters the view direction based on the terrain slope and some objects of interest around the camera position. Each object of interest is suggested to the user by shortly focusing it. The system also ensures that the user is always aware of obstacles that prevent the user from moving. Bares et al. [1] introduce a heuristic constraint solver to create optimal predefined camera paths.

2.3 Physical Motion Models

Physical camera models have shown to be useful in previous approaches, e.g., in [17] a physical model is used to achieve realistic camera movement using 3D input



a) High orientation value b) Reduced orientation value c) Very low orientation value

Figure 1: 3D terrain views with varying orientation values ranging from high to zero.

devices. The concept of dynamic tethering uses a physically-based approach to control the behavior of a camera that traces a moving object or a virtual avatar [3,18].

3. Navigation Framework

The key concepts of our approach include:

- *Orientation Constraints*: They support user orientation by detecting confusing, disorienting view specifications, and they provide functionality to correct them.
- *Physical Motion System*: It ensures steady, continuous camera movements based on decoupling the motion process from handling hardware and user events.

As main input, the framework processes user and time events. Depending on the current *navigation technique,* it generates view specifications, that are checked by orientation constraints and modified, if necessary. The physical motion system uses these view specifications to produce a series of smooth and steady view specifications, that are sent to the underlying 3D rendering system.

4. Orientation Constraints

We need to introduce a measure for the orientation quality of a view specification, and we have to define strategies that take over the control of the camera in situations considered critical.

4.1 Orientation-Supporting Information

Orientation constraints ensure that a view contains a significant amount of orientation-supporting information. For this, we define an *orientation value*, which represents a metric of the orientation-supporting information. This value measures the capability of a view specification to support the orientation of the user. Views with a low orientation value are considered to be confusing and, therefore, to be avoided.

One way to determine the orientation value of a view is to measure the portion of the screen that is covered with relevant parts of the scene. For GeoVEs, the orientation value can be calculated by counting the screen pixels covered by terrain (e.g., using the ARB extension for occlusion query).

For specific application domains, we can define priorities for different types of scene objects that estimate the orientation-supporting contribution of the objects. In the case of geovirtual environments, we can attribute highest priority to landmarks and points of interest, high priority to the terrain surface, and less priority to the sky. This kind of meta information can be specified as attributes in the scene specification.

Figure 1 shows an example of three situations with different orientation values: a) The scene shows enough visible scene content for orientation. b) A smaller portion of the user's sight is covered with orientation-supporting scene objects. c) There is no orientation hint.

4.2 Orientation Maintenance Strategy

Each orientation constraint defines a *maintenance strategy* to hold the orientation value at a sufficiently high level, assuming that the previous view already had a high orientation value. This strategy checks the view specification proposed by the associated navigation technique. If the resulting orientation value falls below a certain threshold value indicating that the user is approaching a disorienting situation, the orientation constraint corrects the view specification. As long as enough orientation-supporting information is provided, the user can transit also through regions of lower interest. As a general functionality, the maintenance strategy checks for collisions of the virtual camera and its environment.

The simplest method to keep a high orientation value is to block the proposed movement by using the previous view specification. Blocking the movement, however, usually leads to disturbing effects.

We propose an improved method, which identifies the user's intention and guides the user away from disorienting views based on the intention and outweighing the degraded orientation with corrections in orthogonal movement degrees.

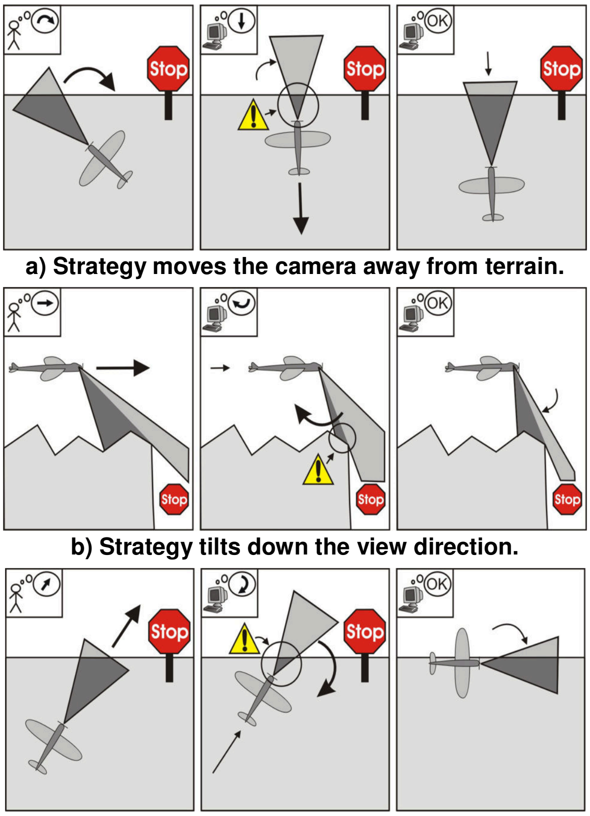
Figure 2 illustrates the maintenance strategy of the Flyer navigation technique in the context of terrain visualization. In three typical situations the user is about to navigate into critical situations:

a) The user rotates the flight direction and causes the camera to look too far beyond the terrain border. The rotation is accepted but outweighed by a slight rear movement away from the border.
b) The user is flying forward beyond the terrain border. The maintenance strategy temporarily tilts down the view direction until a maximum angle is reached.
c) If no more tilting is possible, the strategy rotates the flight direction parallel to the terrain to fly along the terrain border.

4.3 Orientation Adjustment Strategy

Each orientation constraint defines an *adjustment strategy* that ensures that the associated navigation technique is capable of processing the current view specification. While a navigation technique is active, its orientation constraint never produces view specifications that cannot be handled by the technique. After a switch between navigation techniques, however, the newly active navigation technique is confronted with arbitrary view specifications. The orientation adjustment strategy calculates a close applicable view specification if the current one is not usable for the active technique.

Figure 3 illustrates an orientation adjustment strategy for the Zoom navigation technique. After a switch from the Pedestrian technique, no focus point is defined. Since the Zoom technique needs a valid destination to zoom to, the adjustment strategy tilts the view direction until a focus point is hit. During this animation, however, the user will not lose control. The user can interrupt the animation at any time by using a different navigation technique.



a) Strategy moves the camera away from terrain.

b) Strategy tilts down the view direction.

c) Strategy turns right.

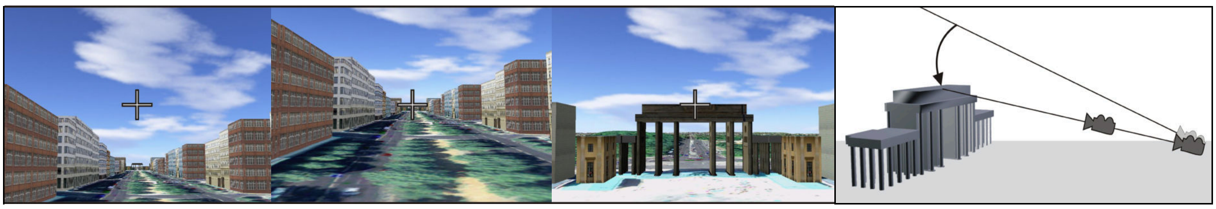
Figure 2: Maintenance strategy for keeping high orientation values.

5. Physical Motion System

The physical motion system regards the camera as a realistic, inertial object within the virtual environment and ensures steady and continuous movement, which is achieved by a series of camera positions with smooth accelerations and decelerations.

5.1 Autonomy of the Motion System

The problem of motion quality is solved at the end of the whole navigation pipeline: the physical motion of the



a) *b)* *c)* *d)*

Figure 3: Adjustment strategy for ensuring of feasible view specifications: a) No valid focus point is defined; b) Adjustment strategy has tilted down the view direction; c) Zoom technique is now able to work; d) Illustration of the adjustment process.

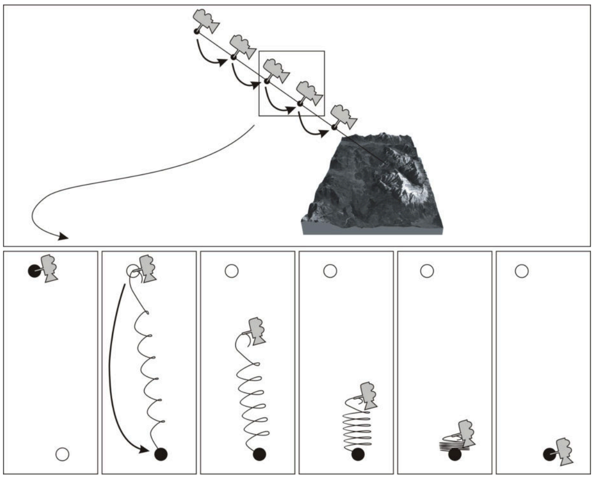


Figure 4: Illustration of the physical spring model applied to the camera.

camera is controlled by a system that is independent from the navigation system.

This separation is motivated by the following reasons:

- Ensuring smooth camera motion in all situations makes up a significant portion of the development effort of navigation techniques and constraints. Encapsulated into a common module, the implementation of navigation techniques and constraints is facilitated.
- The physical motion system is able to smooth the movements that result from the interaction of the camera and its environment. For example, navigation techniques do not need to consider deceleration in the case of an obstacle to which the camera is bound.

5.2 Physics of the Camera Model

We model the camera as an inertial 3D object that is only controlled indirectly via a virtual spring. That is, the user controls only the spring's origin, whereas the camera itself follows to the desired position in a time-delayed way. Unsteady movements of the spring's origin are filtered due to the indirect power transmission and the camera's inertia.

Mathematically, the force of the spring on the camera is described as

$$F_{spring} = S * (pos_{target} - pos_{camera}).$$

Spring strength S and the viscosity V of the medium in which the camera is situated (e.g., vacuum, water, honey) are the parameters, which define the camera's behavior in the physical environment. The viscosity value determines the amount of friction the camera experiences

$$F_{friction} = V * velocity.$$

The mass of the camera can be neglected because as a redundant parameter it does not augment the parameter space by an additional degree of freedom. Mathematically, it can be expressed by the ratio of viscosity and spring strength.

Figure 4 illustrates the physical spring model in the situation of zooming into an area of interest using the mouse wheel as user input-device. Without applying the physical model the camera approaches the terrain in discrete steps (Figure 4 top). Adding the spring induces the following effect (Figure 4 bottom): The unsteady change in position is only applied to the spring's origin. The camera itself relaxes in a spatial-coherent way to its new target position. Newton's physical laws guarantee steadiness in position *and* velocity:

$$F_{inertia} + F_{spring} + F_{friction} = 0$$
$$F_{inertia} = mass * acceleration$$

Mathematically, the behavior of the camera is obtained by solving the resulting motion equation

$$acceleration + V * velocity + S * (pos_{target} - pos_{camera}) = 0.$$

Spring strength S and viscosity V determine the exact behavior. The stronger the spring and the lower the viscosity value the faster is the camera's movement. The two parameters also determine a) whether the camera oscillates around the new target point, b) whether it performs only a single oscillation (critical damping), or c) whether the camera reaches the target without passing it. The viscosity depending critical spring value $S_{critical}$ separates the domain of movement with oscillations around the target point ($S > S_{critical}$) and the domain of direct movement into the target without oscillation ($S < S_{critical}$). It is given by the formula

$$S_{critical} = 2 * \sqrt{V}.$$

The appropriate choice of the parameters S and V is important for the user acceptance of a navigation technique, because they define a compromise between the degree of smoothness and the time lag between the user input and the camera movement. Therefore, each navigation technique requires its special physical behavior of the camera. For the Trackball navigation technique, e.g., the camera needs to follow the spring's origin in a direct and tight way. For it, a strong spring is adequate. For the Flyer navigation technique, best user acceptance can be achieved if the motion appears exceptionally smooth, which is obtained by a weak spring. A *physical setting* is associated with each navigation technique in the navigation framework, containing suitable parameters for the physical environment. Navigation techniques switch parameters of the physical system without reinitializing it. Hence, a steady visual flow is guaranteed even in the case of switches between techniques.

5.3 Resolving Conflicts During Movement

The camera specifications produced by the physical motion system can be in conflict with the applied constraints of the navigation system. However, these conflicts rank below the motion quality because the camera follows the target instantly, and potential violations of constraints only occur for a short time.

In Figure 5 the camera is flying over a terrain surface at a fixed height. If we would directly assign the intended height to the camera, it would follow each bump of the terrain surface. The resulting movement, of course, would be very unpleasant. The physical motion system enhances the quality of the camera motion by filtering the fast changes in height due to physical inertia of the camera. The resulting camera path is a smoothed version of the terrain surface. The filtering process is time dependent, i.e., it depends on the velocity of changes in height and not only in the surface's height profile. Only flying fast will result in a smoothed camera trajectory; flying with a low velocity will approximately reproduce the original terrain surface. Additionally, we scale the velocity proportional to the camera's height above terrain, in analogy to the Depth Modulated Flying of Ware and Fleet [19]. Therefore, the impact of the terrain profile decreases with increasing height.

To improve the sensitivity of the physical motion system with respect to the camera-environment interaction, we can also consider anticipating camera movements. For example, the application of the physical motion can interfere with the property of the Flyer navigation technique to keep the camera at a fixed height – temporary collisions are likely to occur because of the camera's inertia. The anticipatory method measures the to-be-heights of the terrain in the flying path before the camera reaches these points. It adjusts the camera's intended height to the maximum of all measured values. As a result, collisions of the camera with the terrain are prevented. Figure 5d shows the resulting camera path with the anticipatory method.

Nevertheless, in rare cases the camera still might temporarily collide with the terrain or objects in the 3D world. A final collision test prevents collisions in this case. The camera's final position will then be modified.

5.4 Fast Slow-Down of the Physically-Based Motion

A crucial situation occurs when the camera reaches its destination and the user stops the interaction, for example, if the camera is pointing onto an object of interest. A disadvantage of the physical motion model is the reaction time of the camera when choosing an environment setting with a weak spring. While the camera is already in its optimal position, the force's origin is yet one step further. As a result, the camera will come to rest later than desired. To avoid this problem the physical system has a built-in slow down control. When it is activated by a navigation technique the viscosity of the medium in which the camera is situated is set to a very high value. This is comparable to an exchange of the current medium by a very viscous one like honey. Nearly all of the motion energy is absorbed by the high friction and the camera is slowed down rapidly, but still in a steady and pleasant way. Additionally the spring-force's origin is moved to the actual camera position so that the camera will not be pulled away from its optimal position.

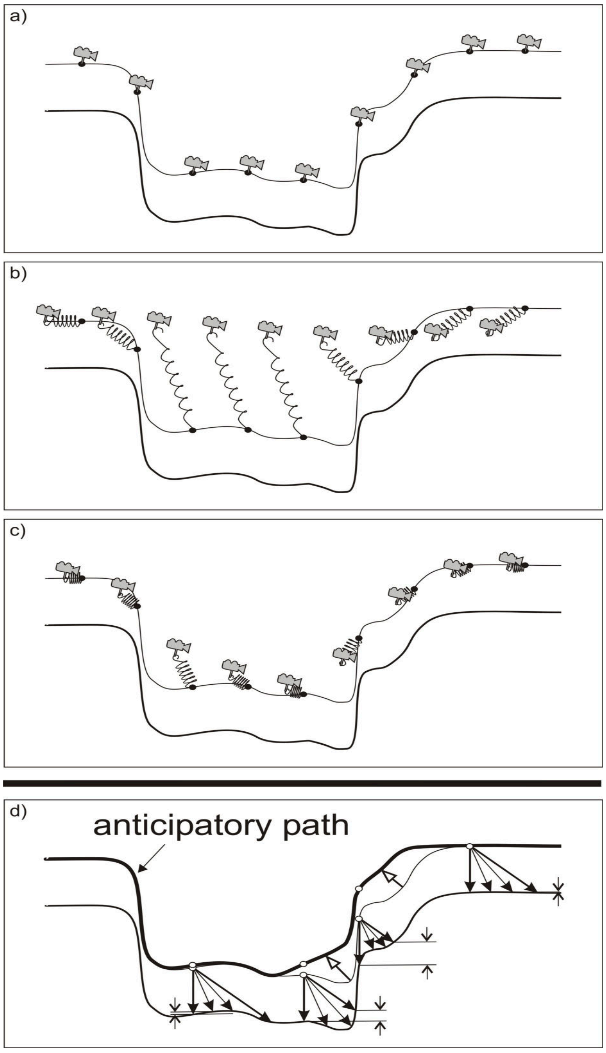


Figure 5: The Flyer navigation technique and the interaction of camera and terrain surface. a) Flight without the physical motion system. b) Flight at high velocity. c) Flight at low velocity. d) Flight based on anticipating the path.

6. Conclusions

Smart and physically-based navigations contribute to solve typical usability problems in the scope of virtual environments such as the "get lost" and "end-of-world" interaction problems. We observed that orientation constraints require domain-specific knowledge as illustrated for the case of geovirtual environments. In other domains, the framework can facilitate the development of similar constraints improving effectiveness and intuition.

In our experience, the physically-based motion model improves the motion quality regardless of the frame rate provided that 3D rendering is done in real-time. It handles even complex situations, e.g., if switches between different navigation techniques take place, or if events such as collision with objects of the virtual world are considered.

Our approach has been implemented as a part of our 3D geovisualization system LandXplorer. As future work, we plan on doing usability studies to examine the effect of different orientation constraints and physical settings. Furthermore, we will specialize the framework for the domain of 3D city models. As a major area of future work, we want to work on a more sophisticated definition of the orientation value as a metric of the orientation support by considering the semantics of the 3D scene objects.

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